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TECHNICAL NOTE 3660

INVESTIGATION OF THE Ni_3Al PHASE OF NICKEL-ALUMINUM ALLOYS

By Edward M. Grala

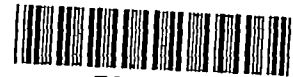
Lewis Flight Propulsion Laboratory
Cleveland, Ohio



Washington

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TECHNICAL NOTE 3660

INVESTIGATION OF THE Ni_3Al PHASE OF NICKEL-ALUMINUM ALLOYS

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SUMMARY

An investigation was made to determine the effects of homogenization treatments and of composition on the tensile properties of as-cast alloys in the Ni_3Al -intermetallic-phase region.

The 13.3-percent-aluminum alloy had an average as-cast room-temperature tensile strength of 28,650 psi with 1.0-percent elongation. After homogenization treatments at 1800°F , the room-temperature tensile strength decreased to 20,350 psi with 0.2-percent elongation. An alloy in the Ni_3Al -phase region containing 14 percent aluminum had better tensile properties than the stoichiometric composition (13.3 percent aluminum); the average as-cast room-temperature tensile strength was 39,250 psi, and the homogenized tensile strength was 32,100 psi. At 1500°F the average tensile strength for the 14-percent-aluminum alloy was 19,600 psi.

The stoichiometric Ni_3Al was not "hot-workable" and had moderate impact strength. The stress-rupture strengths were evaluated at 1500° , 1600° , and 1700°F for the 14-percent-aluminum alloy. The 100-hour rupture strength was interpolated as 8600 psi at 1500°F .

INTRODUCTION

Many intermetallics such as NiAl and Ni_3Al are of interest for high-temperature application because they have high melting points and are stable at high temperatures. In reference 1 the intermetallics NiAl and Ni_3Al are discussed on the basis of properties obtained from as-cast specimens. These were cored and also contained a secondary structure. The Ni_3Al intermetallic phase was shown to have a slight amount of room-temperature ductility.

In this investigation, the properties of Ni_3Al were determined before and after homogenization. The properties obtained are also compared with the as-cast properties of Ni_3Al at room temperature reported in reference 1. Two compositions with the Ni_3Al range were studied (fig. 1). These were alloys of 13.3 and 14.0 percent aluminum by weight. In addition, the hot-workability of the stoichiometric (13.3 percent aluminum) Ni_3Al phase was studied by rolling and swaging experiments.

MATERIALS, APPARATUS, AND PROCEDURE

Specimen Preparation

Materials. - Electrolytic nickel chips (99.95 percent by weight nickel) and 1-inch cubes of high purity aluminum (99.85 percent by weight) were used in the preparation of the experimental compositions.

Alloy compositions. - The desired compositions and the analyses are shown in table I.

Casting

A description of the casting techniques employed are given in reference 1. The following changes were made in this investigation:

(1) The nickel was placed at the top of the charge in the crucible rather than at the bottom. This change resulted in a melt with a cleaner appearance.

(2) The holding time was increased to 2 minutes to allow the melt to subside more completely.

(3) A larger "hot top" was used with the same copper mold to avoid pipe. Typical castings are shown in figures 2(a) to (c).

Heat-Treating

A conventional Globar furnace with an air atmosphere was used for heat treatments and for heating prior to mechanical working. The specific treatments will be mentioned during the discussions of the specific effects studied.

Hot-Rolling

Three specimens of the 13.3-percent-aluminum alloy were used to study the rolling behavior. In order to insure homogeneity and structural stability, the specimens were heated at 2200° F for 48 hours prior to rolling. The ingot size was 1- by 1- by 3-inches (fig. 2(b)). The ingots were rolled in a 4-high rolling mill with $2\frac{1}{2}$ -inch-diameter working rolls. The specimens were soaked for 1 hour at the rolling temperature. It took about 3 seconds to move the specimen from the furnace to the rolls.

Hot-Swaging

Two specimens of the 13.3-percent-aluminum alloy were used to study the swaging behavior. Round tapered ingots shown in figure 2(c) were homogenized at 2200° F for 48 hours and ground to 0.750-inch diameter. The ingots were preheated for 1 hour prior to swaging.

Machining

Cylindrical surfaces were ground using silicon carbide wheels. However, the grinding of flat surfaces with silicon carbide resulted in badly checked surfaces and severe edge cracking. Flat surfaces, free of cracks and grinding checks were produced using the following:

- (1) Abrasive: aluminum-oxide, 46-mesh, vitreous-bonded, soft grinding wheel
- (2) Coolant: water and soluble oil
- (3) Speed: slow-to-average table speed with a grinding wheel speed of 2300 to 2600 surface feet per minute

Inspection

All physical test specimens were inspected by radiography and post-emulsifier penetrant oil. Radiography showed that internal defects occur very rarely. Specimens were discarded if surface defects were found.

Specimen Evaluation

Short-time tensile evaluation. - Because of the ease of preparation and suspected low ductility of the alloys, conical-end specimens (fig. 2(d)) were used. These specimens had a $1/4$ -inch-diameter gage section and a $1\frac{1}{4}$ -inch gage length. A conventional tensile machine was used, and room-temperature stress-strain curves were obtained by means of a recording extensometer. The loading rate was 4000 psi per minute for all tests. The proportional limit was determined from the "break" in the stress-strain curve (see fig. 3) and was used as the yield strength. For high-temperature evaluations, the specimens and holders were enclosed in a platinum-wound tube furnace and the elongation was measured after fracture. All tensile tests were performed in air.

Stress-rupture evaluation. - Conical-end, stress-rupture specimens identical in design to those used in the tensile evaluations were run at 1500° F in an air atmosphere using the procedure described in reference 2. All specimens were homogenized at 1800° F for 48 hours before evaluation.

Structure determination. - A high-angle X-ray diffractometer was used to obtain diffraction patterns for solid specimens. A rotating, flat specimen holder was used to reduce orientation effects. All X-ray patterns were made using copper $K\alpha$ radiation with a nickel filter and a scanning rate of $1^{\circ} 2\theta$ per minute, and 1 inch on the chart equal to $2^{\circ} 2\theta$. Patterns were made for the alloys in the as-cast and homogenized (1800° F for 48 hr) conditions. Lattice parameters were calculated by averaging the lattice parameters calculated from each diffraction maximum. The purpose was to compare the as-cast and homogenized structures.

Density evaluation. - Densities were determined by weighing the specimens in air and water.

Impact evaluation. - Impact tests were run on $3/16$ - by $3/16$ - by $1\frac{1}{2}$ -inch bars of the 13.3-percent-aluminum alloy that had been homogenized at 1800° F for 48 hours. The tester was a modified Bell Telephone Laboratory Izod impact tester (fig. 4) with a total capacity of 25.5 inch-pounds. The specimen is held in testing position by a vise. The gripping force was applied by a dead weight load exerted on the specimen through a lever system. The force on the specimen was 300 pounds. The specimen is located so that it is struck $1/8$ inch from the free end. Impact energies reported are obtained in the conventional manner, that is, by using the difference between the initial and final energies of the pendulum, and making allowances for friction losses.

RESULTS AND DISCUSSION

Effects of Casting Method

3910 Both compositions covered by this report were easily cast. The ingots were free of porosity and pipe. However, the room-temperature as-cast tensile strength for the 14-percent-aluminum alloy was reduced about 19 percent, from an average of 48,250 psi with 1.7-percent elongation (ref. 1) to an average of 39,250 psi with 1.2-percent elongation (table II), by the alteration in casting technique. This decrease in strength and ductility can possibly be explained on the basis of differences in the cooling rates and the resultant microstructures. The present procedure involves the use of a larger hot top which results in a slower cooling rate for the ingot. The slower cooling rate produces a coarser structure. This coarsening can be seen by comparing figures 5(a) and (b) with figures 5(c) and (d). Evidently there is a larger amount of the secondary structure and the shape of this secondary structure is more plate-like in the 14-percent-aluminum alloy reported in reference 1 than in the alloys reported in this study. The differing distribution of this secondary structure in the two as-cast 14-percent-aluminum alloys may be affecting the strength and ductility.

The change in tensile properties is paralleled by a change in hardness. The original casting procedure (ref. 1) resulted in a hardness of Rockwell A-62 (table III) for the 14-percent-aluminum alloy, while the present procedure resulted in a hardness of Rockwell A-57 (table III) for the same alloy. It is evident that the as-cast mechanical properties are very sensitive to ingot cooling rate. As investigation was to study the properties of the homogenized intermetallic compound, further reasons for the differences in as-cast strength were not investigated.

Hot-Workability of Stoichiometric Ni_3Al

It is shown in reference 1 that the as-cast 14-percent-aluminum alloy was "hot short" at 2000° and 2400° F. In this study, ingots of the 13.3-percent-aluminum alloy were homogenized at 2200° F to produce a structure which would be stable at the rolling temperatures. All attempts to hot-roll and hot-swage this alloy failed. Results are listed in tables IV and V.

Mechanical Properties

Effect of homogenization on tensile strength and hardness. - Heat treatments which homogenized the dendritic structure decreased the tensile strength and elongation of both the 13.3- and 14-percent-aluminum alloys (table II and figure 3). The average room-temperature tensile

strength of the as-cast 13.3-percent-aluminum alloy decreased from 28,650 psi with 1.0-percent elongation to 20,350 psi with 0.2-percent elongation by homogenization treatment at 1800° F; the tensile strength at 1500° F was 10,900 psi. The average room-temperature tensile strength of the as-cast 14.0-percent-aluminum alloy decreased from 39,250 psi with 1.2-percent elongation to 32,100 psi with 0.4-percent elongation after homogenization; the tensile strength at 1500° F was 19,600 psi. The decreases in elongation were unexpected since it was thought that a homogeneous structure would improve ductility. A possible explanation for the loss in strength for the Ni_3Al phase from as-cast to homogenized condition is that since the secondary structure is not continuous it is strengthening the material by a dispersion strengthening effect (fig. 6). However, the loss in strength would be expected to be accompanied by a decrease in hardness. The 14-percent-aluminum alloy did show a slight decrease in hardness, from Rockwell A-57 to Rockwell A-55 (table III), but the 13.3-percent-aluminum alloy showed a slight increase in hardness, from Rockwell A-53 to Rockwell A-55 (table III), when homogenized at 1800° F.

Effect of grain size. - Preliminary tests indicated that the hardness of both alloys (table III) decreased as the grain size increased. The 14-percent-aluminum alloy was chosen for further study of this effect because it was stronger and had greater ductility. Heat treatment at 2200° F resulted in grain coarsening (fig. 7). The coarse grains decreased the room-temperature tensile strength and ductility from 32,100 psi with 0.4-percent elongation to an average of 26,250 psi with 0.2-percent elongation (table II). The 1500° F tensile strength decreased from an average of 19,600 to 9,900 psi (table VI).

Effect of composition. - Little change in tensile properties might be expected for small compositional changes within the Ni_3Al -phase region. However, the data indicate large changes in both room- and elevated-temperature strengths (tables II and VI). At room temperature the 14-percent-aluminum alloy is approximately 58 percent stronger than the 13.3-percent-aluminum alloy; at 1500° F, the 14 percent aluminum is 80 percent stronger. This increase in strength is not reflected in the hardness since both alloys are of approximately the same hardness (table III). These results show that the strengths of intermetallics may be very sensitive to slight changes in composition.

Effect of temperature. - Elevated-temperature tensile strength of Ni_3Al (table VI) does not decrease rapidly with increasing temperature. This can be noted (fig. 8) by comparing the rate of reduction in strength with that of conventional, single-phase, nickel-base alloys such as Inconel (ref. 3). The rate of decrease in strength with increasing temperature for Ni_3Al is considerably less than for Inconel.

Impact strength. - The impact strength of stoichiometric Ni_3Al is compared to several high-temperature materials as follows:

Material	Impact strength, in.-lb
Ni_3Al^a (13.3 percent aluminum)	16.2 13.0 10.4 10.3
K-152B ^a	2.5
K-162B ^a	4.4
Infiltrated titanium ^{b,c} carbide cermet TC-66-I	9.0
X-40 ^{b,d}	48.05

^aUnnotched.

^bNotched.

^cData from unpublished report of Thompson Products, Inc.

^dRef. 1.

While the values shown in the preceding table were obtained under differing test conditions, they are believed to be similar enough to be used for comparison purposes. The Ni_3Al is superior to the cold pressed and sintered titanium carbide cermets (K-152B and K-162B), similar to the infiltrated cermets, and inferior to the high-temperature alloy X-40.

Stress-rupture. - Because the 14-percent-aluminum alloy had greater strength at both room temperature and 1500° F, the stress-rupture strength of only this alloy was determined. These data are shown in table VII. The 100-hour stress-rupture life at 1500° F was interpolated as 8,600 psi. The single-point-rupture data in table VII at 1600° and 1700° F show that the rupture strength of the alloy does not fall off rapidly with increasing temperature. Because the fractured halves of the stress-rupture bars could not be fitted together, the stress-rupture ductility could not be determined.

Type of fracture. - In all tensile-strength, stress-rupture, and impact tests at room and elevated temperatures, the fracture faces were fibrous (fig. 9) and the fractures were intergranular. The fibrous nature of the fracture is further indicated by the fact that after fracture

the ends of the test bars could not be fitted together. In most tensile tests the material would fracture and additional motion of the test machine was required to separate the ends of the bar (as shown in fig. 9(c)).

As stated previously the impact strength of Ni_3Al is similar to that of some of the cermets; however, the fracture is fibrous (fig. 9(d)) rather than brittle as in the case of the cermets.

Microstructure of Ni_3Al

Phase identification. - The lattice parameters of the 13.3- and 14-percent-aluminum alloys in the as-cast and homogenized conditions are listed in table III. Within the accuracy of the measurements, the parameters fall within the range for Ni_3Al reported in reference 4. All lines in the patterns for the homogenized alloys and for the as-cast 14-percent-aluminum alloy correspond to those of Ni_3Al . There was, however, one weak line in the as-cast 13.3-percent-aluminum alloy which did not correspond to the Ni_3Al pattern. The line corresponds to the strong (111) nickel line. Changes in the lattice parameter and density (table III) show that the density decreases and the lattice parameter increases with heat treatment.

From the phase diagram (fig. 1) it is evident that the 13.3- and 14-percent-aluminum alloys should form the Ni_3Al phase by different mechanisms. The structures of the as-cast alloys tend to confirm this. In the 14-percent-aluminum alloy a plate-like structure (see fig. 10(c)) can be noted in the secondary phase. This may be the result of the transformation of NiAl that was retained during the chill casting to Ni_3Al .

In the 13.3-percent-aluminum alloy, the diffraction pattern contained an unidentified line which appeared to be the (111) nickel reflection. On chill casting this composition, a small amount of the terminal nickel solid solution (γ in fig. 1) might be retained and might account for the unidentified line observed in the pattern.

Results of homogenization treatments. - A dendritic structure is evident in the as-cast structures of both compositions (figs. 5(a), (b), and 6(a)). The temperature at which the secondary structure disappeared was determined for both alloys. In figures 6 and 10, the solution of the secondary structure in the stoichiometric Ni_3Al (13.3 percent aluminum) phase can be followed. Partial solution of the secondary structure begins at 1600°F , and only a little remains after a homogenization treatment at 1700°F . At 1800°F , the material is a uniform one-phase structure. At 2000°F , grain growth started to take place and coarsening continued at 2200°F .

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The as-cast structure of the 14-percent-aluminum alloy was different from the 13.3-percent-aluminum alloy in that the 14-percent-aluminum alloy has a larger amount of secondary structure present (figs. 5(a) and 6(a)), and the size and shape of secondary structure is different (figs. 5(b) and 10(a)). In this alloy, fine plate-like precipitate within the secondary structure is shown in figure 7(c). Homogenization treatments at 1800° F cause the solution of the secondary structure and produce a uniform one-phase structure (fig. 7(a)). Heat treatment at 2200° F causes a coarsening of the as-cast grain size (fig. 7(b)). Grain boundaries are not visible in the as-cast structure because it was etched only lightly to show the secondary structure.

SUMMARY OF RESULTS

Two nickel-aluminum alloys within the Ni_3Al -phase field were studied. The following data were obtained:

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1. The average as-cast room-temperature tensile strength of the 13.3-percent-aluminum alloy was 28,650 psi with 1.0-percent elongation. Homogenization treatments at 1800° F caused a decrease in tensile strength and ductility to 20,350 psi with 0.2-percent elongation. At 1500° F, the homogenized alloy had a tensile strength of 10,900 psi.
 2. The 14-percent-aluminum alloy had an average as-cast room-temperature tensile strength of 39,250 psi with 1.2-percent elongation. Homogenizing at 1800° F caused a decrease in strength to 32,100 psi with 0.4-percent elongation. The homogenized 14-percent-aluminum alloys all had a tensile strength of 19,600 psi at 1500° F.
 3. Coarse grain size has a deleterious effect on the tensile properties of the Ni_3Al intermetallic. Heat treatment of the 14-percent-aluminum alloy at 2200° F produced a coarse grain size and decreased the room-temperature tensile strength from 32,100 psi with 0.4-percent elongation to 26,250 psi with 0.2-percent elongation. The 1500° F tensile strength decreased from 19,600 psi to 9,900 psi for the coarse-grained structure.
 4. The stoichiometric Ni_3Al intermetallic phase could not be hot-rolled or hot-swaged.
 5. The 100-hour rupture strength of the homogenized 14-percent-aluminum alloy was interpolated as 8,600 psi at 1500° F.

CONCLUDING REMARKS

The tensile strengths at room and elevated temperatures and ductility of the intermetallic Ni_3Al are very sensitive to composition structure and grain size.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, January 4, 1956

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2. Maxwell, W. A., and Sikora, P. F.: Stress Rupture and Creep Testing of Brittle Materials. Metal Prog., vol. 62, no. 5, Nov. 1952, pp. 97-99.
3. Anon.: Engineering Properties of Inconel. Tech. Bull. T-7, Dev. and Res. Div., The International Nickel Co., Inc., Mar. 1943.
4. Taylor, A., and Floyd, R. W.: The Constitution of Nickel-Rich Alloys of the Nickel-Titanium-Aluminum System. Jour. Inst. Metals, vol. 81, May 1953, pp. 451-464.

TABLE I. - CHEMICAL ANALYSIS OF SPECIMENS

Desired composition		Actual composition, percent by weight			
Percent by atoms	Percent by weight	Ni	Al	Fe	Si
75 Ni + 25 Al	86.7 Ni + 13.3 Al	86.70	13.50	0.04	None
73.6 Ni + 26.4 Al	86 Ni + 14 Al	86.0	13.93	0.05	None

TABLE II. - ROOM-TEMPERATURE TENSILE PROPERTIES
OF INTERMETALLIC Ni₃Al

Composition, percent by weight		Condition	Yield strength, psi	Tensile strength, psi	Extensometer elongation, percent
Ni	Al				
86.7	13.3	As-cast	12,000	30,600	1.1
86.7	13.3	As-cast	13,000	26,700	.9
86.7	13.3	Homogenized at 1800° F for 48 hr	10,000	22,200	0.2
86.7	13.3	Homogenized at 1800° F for 48 hr	12,500	18,500	.2
86	14	As-cast		^a 50,600	
86	14	As-cast	^a 15,000	^a 45,900	1.7
86	14	As-cast	15,500	39,500	1.2
86	14	As-cast	14,000	39,000	1.2
86	14	Homogenized at 1800° F for 48 hr	22,000	32,100	0.4
86	14	Homogenized at 1800° F for 48 hr	21,000	32,100	.4
86	14	Homogenized at 2200° F for 48 hr	22,500	26,600	0.1
86	14	Homogenized at 2200° F for 48 hr	21,000	25,900	.2

^aRef. 1.

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TABLE III. - EFFECT OF 48-HOUR HOMOGENIZATION TREATMENTS ON MICROSTRUCTURE OF INTERMETALLIC Ni₃Al

Composition, percent by weight		Homogenization temperature, °F	Effect on grain size	Hardness, Rockwell A-	Figure	Metallographic examination of microstructure	Density, g/ml	Lattice parameter, Kx units
Ni	Al							
88.7	13.3	As-cast	-----	53	6(a) 10(a)	Two phases, one phase present in dendritic pattern ^a	7.48	3.561
86.7	13.3	1600	None	54	6(b) 10(b)	Partial solution of dendritic phase	----	-----
86.7	13.3	1700	None	56	6(c) 10(c)	Only small amount of dendritic phase retained	----	-----
86.7	13.3	1800	None	55	6(d) 10(d)	One phase	7.43	3.564
86.7	13.3	2000	Some grain growth	52	-----	One phase	----	-----
86.7	13.3	2200	Coarse grain	48	-----	One phase	----	-----
88	14	As-cast ^b	-----	62	7(c)	Two phases, sec- ondary pre- ferred phase has some orientation	7.39	3.573
86	14	As-cast	-----	57	7(c)	Two phases, sec- ondary phase randomly oriented	7.37	3.558
86	14	1600	None	55	7(a)	One phase	7.35	3.568
86	14	2200	Coarse grain	49	7(b)	One phase	----	-----

^aTentative identification of nickel solid solution.^bRef. 1.

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TABLE IV. - HOT-ROLLING OF STOICHIOMETRIC Ni_3Al

Specimen	Rolling temperature, $^{\circ}\text{F}$	Rolling behavior	Passes before cracking	Average reduction per pass, percent	Remarks
1	2000	Poor	2	0.7	No cracks after first pass. Edge cracks after second pass
2	2200	Poor	2	0.7	No cracks after first pass. Large edge cracks on both edges after second pass
3	2400	Poor	1	0.6	Large edge cracks both edges

TABLE V. - HOT-SWAGING OF STOICHIOMETRIC Ni_3Al

Specimen	Swaging temperature, $^{\circ}\text{F}$	Number of passes	Diameter of unswaged bar, in.	Diameter of swaged bar, in.	Reduction in area, percent	Remarks
1	2200	1	0.750	0.742	2.0	Cracks normal to axis of bar.
2	2200	1	0.750	0.741	2.3	Cracks normal to axis of bar.

TABLE VI. - ELEVATED-TEMPERATURE TENSILE STRENGTHS
OF INTERMETALLIC Ni₃Al

Composition, percent by weight		Homogenization treatment		Tensile strength, psi	Test temperature, °F
		Temperature, °F	Time, hr		
Ni	Al				
86.7	13.3	1800	48	11,800	1500
86.7	13.3	1800	48	10,700	1500
86.7	13.3	1800	48	10,200	1500
86.7	13.3	1800	48	12,450	1700
86.7	13.3	1800	48	10,700	1700
86.7	13.3	1800	48	9,350	1800
86.7	13.3	1800	48	7,450	1800
86	14	1800	48	19,700	1500
86	14	1800	48	19,500	1500
86	14	2200	48	9,900	1500

TABLE VII. - STRESS-RUPTURE PROPERTIES OF
HOMOGENIZED NICKEL-ALUMINUM ALLOY
CONTAINING 14 PERCENT ALUMINUM

Stress, psi	Life, hr	Test temperature, °F
10,000	61.2	1500
7,500	159.5	1500
5,000	668.8	1500
5,000	163.3	1600
5,000	57.7	1700

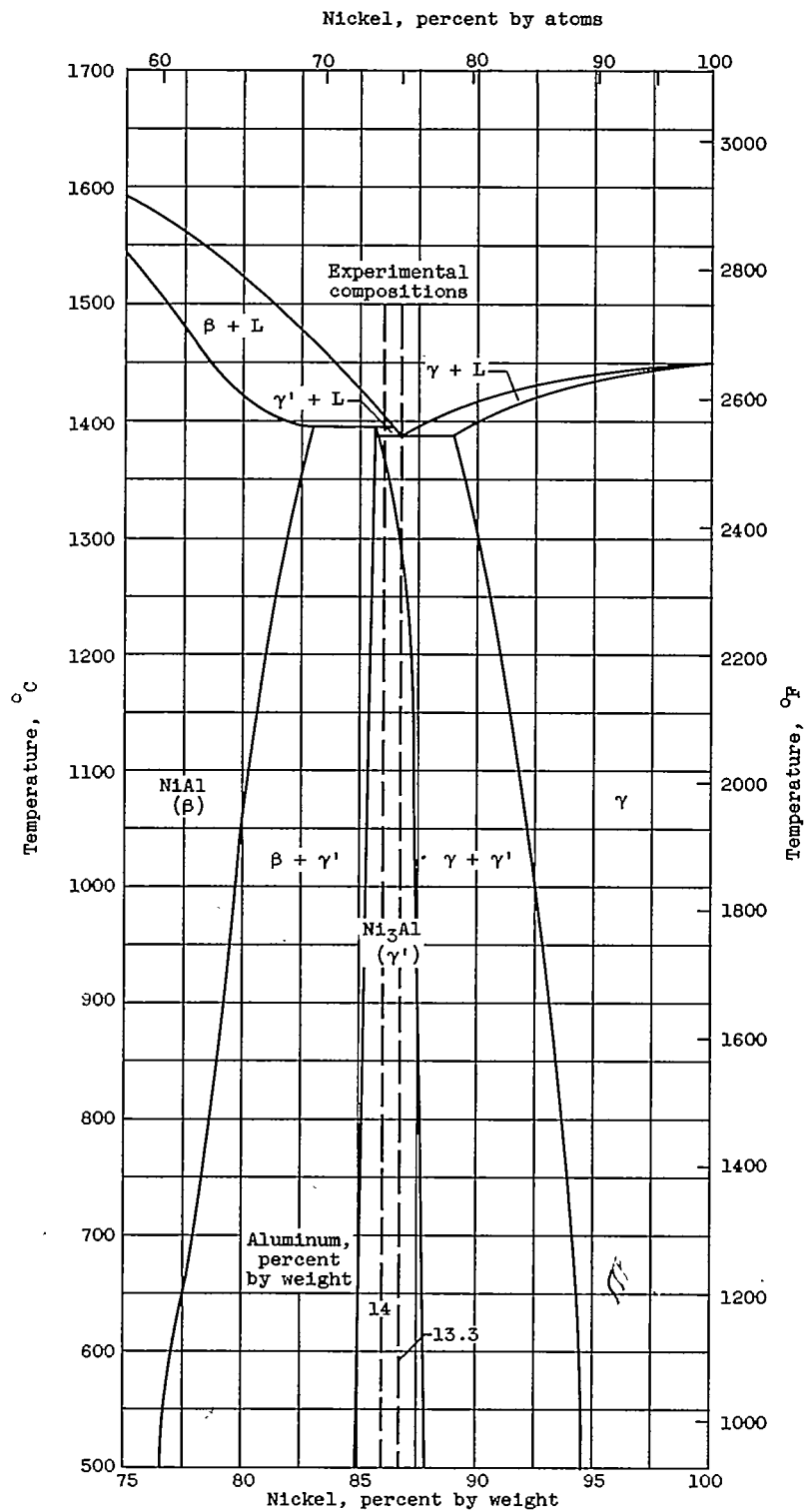
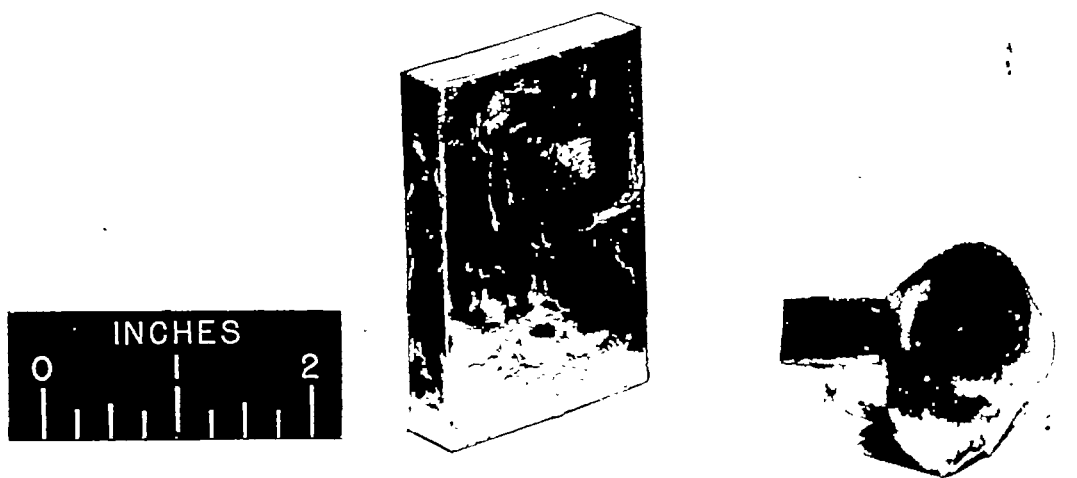


Figure 1. - Enlarged view of area under investigation taken from phase diagram of nickel-aluminum system (ref. 4, p. 26).



(a) 1/2- By 2-inch ingot.



(b) 1- By 1-inch ingot.

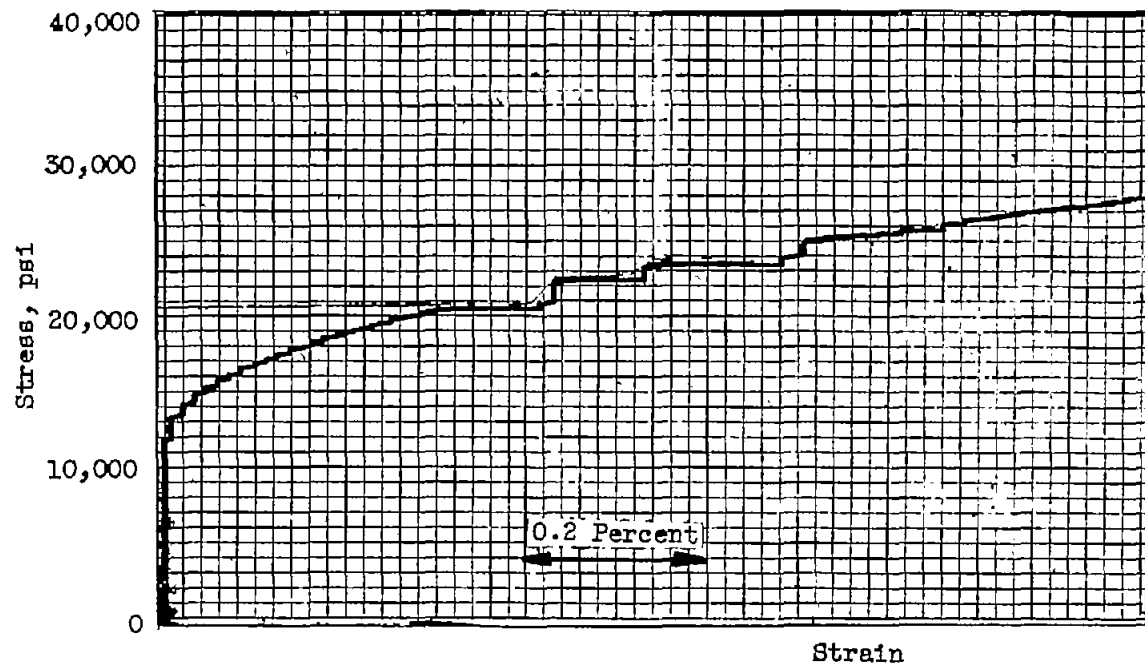


(c) 1-Inch round tapered ingot.

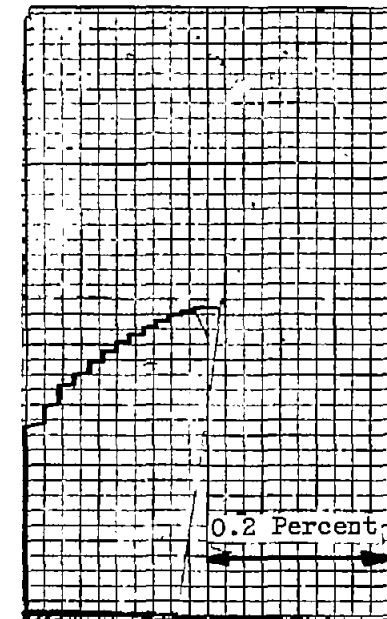


(d) Ground tensile bar.

Figure 2. - Typical Ni₃Al specimens.



(a) As-cast.



(b) Homogenized. Temperature, 1800° F; time, 48 hours.

Figure 3. - Representative extensometer stress-strain curves for stoichiometric Ni₃Al at room temperature.

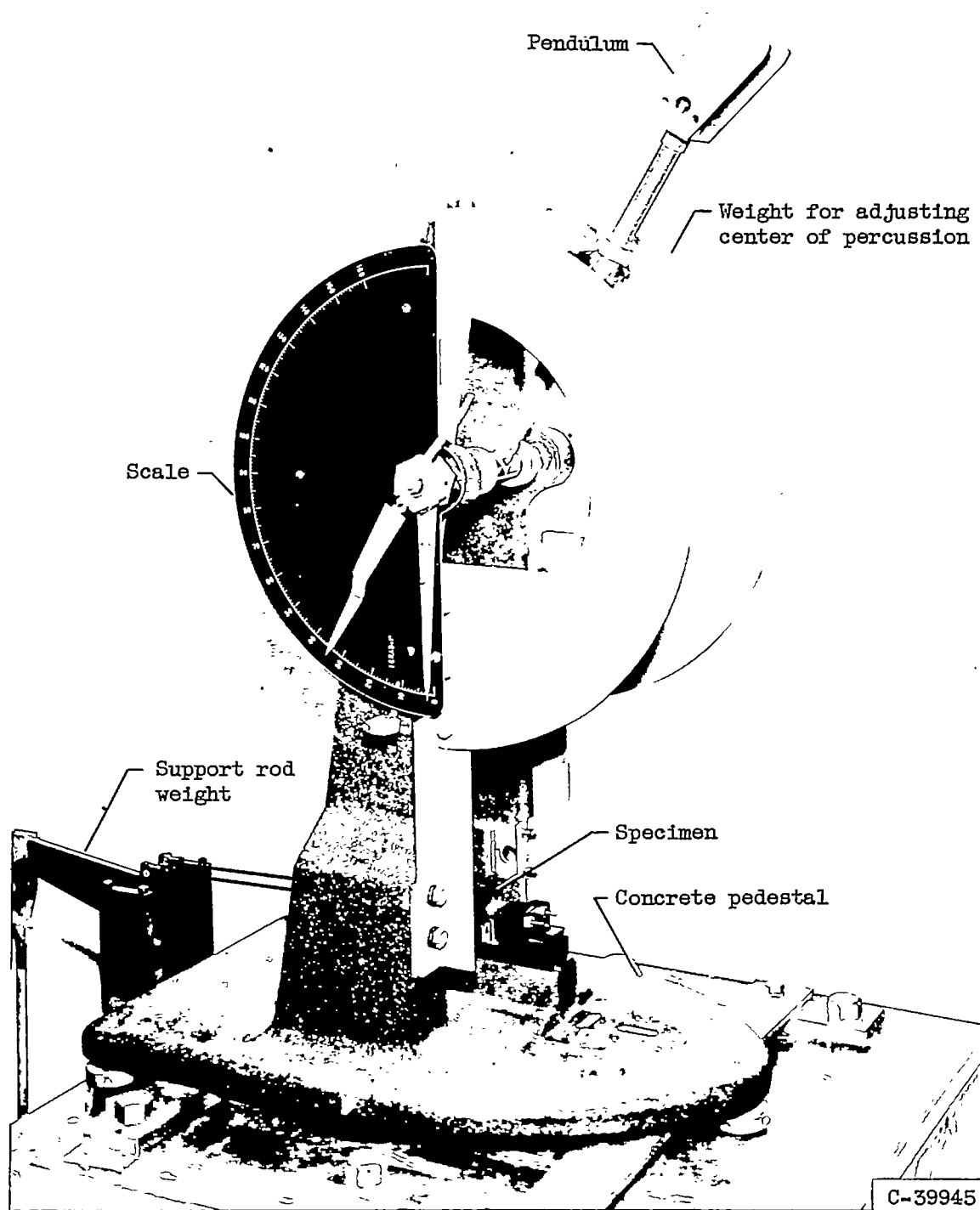
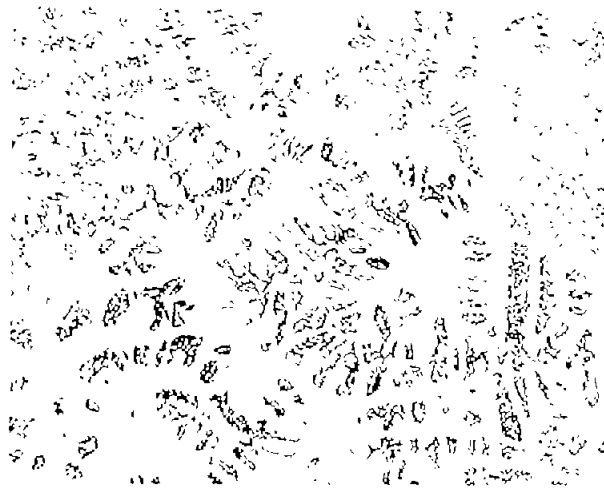


Figure 4. - Impact testing apparatus.



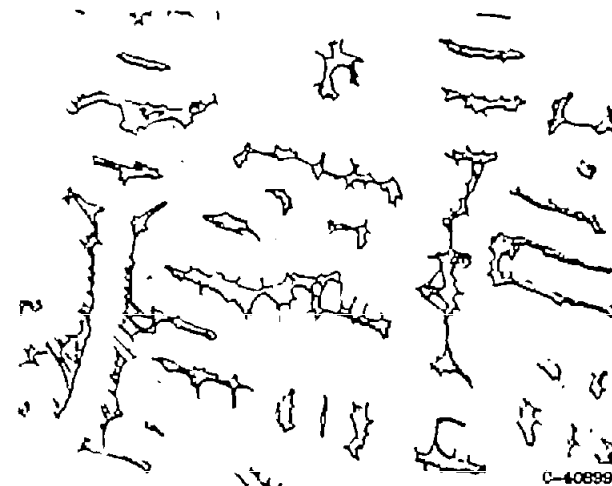
(a) As-cast, X100.



(b) As-cast, X500.



(c) As-cast, X100 (ref.1).



(d) As-cast, X500 (ref.1).

Figure 5. - As-cast microstructure of 14-percent-aluminum alloy (Ni_3Al phase). Etchant, 1 part hydrogen tetrafluoride, 4 parts glycerine, and 4 parts water.

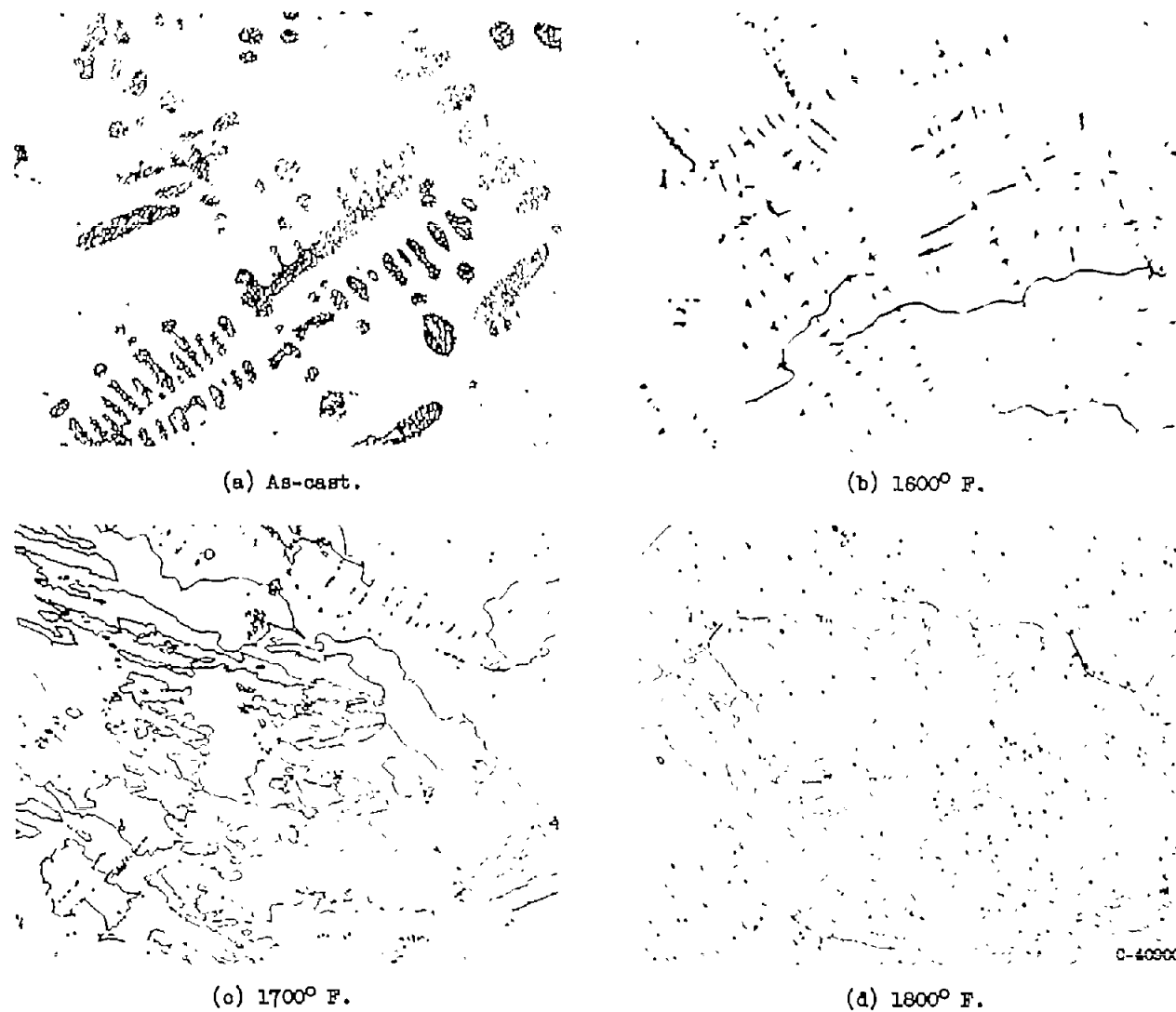
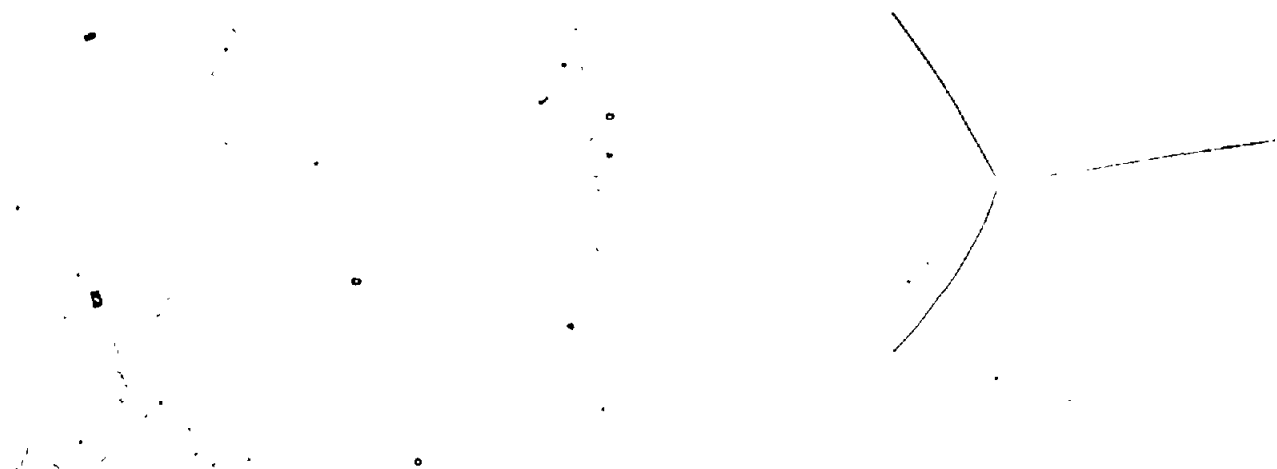
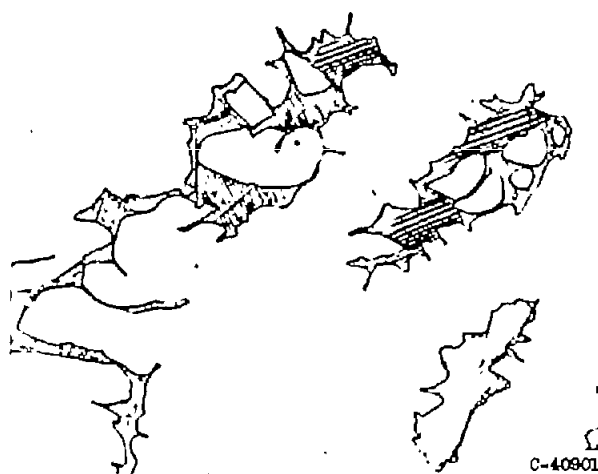


Figure 6. - Effects of 48-hour homogenization treatments at various temperatures on microstructure of stoichiometric (13.3 percent aluminum) Ni_3Al . Etchant, 1 part hydrogen tetrafluoride, 4 parts glycerine, and 4 parts water; $\times 100$.



(a) 1800° F for 48 hours, x500.

(b) 2200° F for 48 hours, x500.



(c) As-cast. Etchant, cupric chloride saturated with hydrochloric acid, nitric acid, and alcohol.

Figure 7. - Effects of 48-hour homogenization treatment at various temperatures on microstructure of 14-percent-aluminum alloy (Ni₃Al phase). Etchant, 1 part hydrogen tetrafluoride, 4 parts glycerine, and 4 parts water.

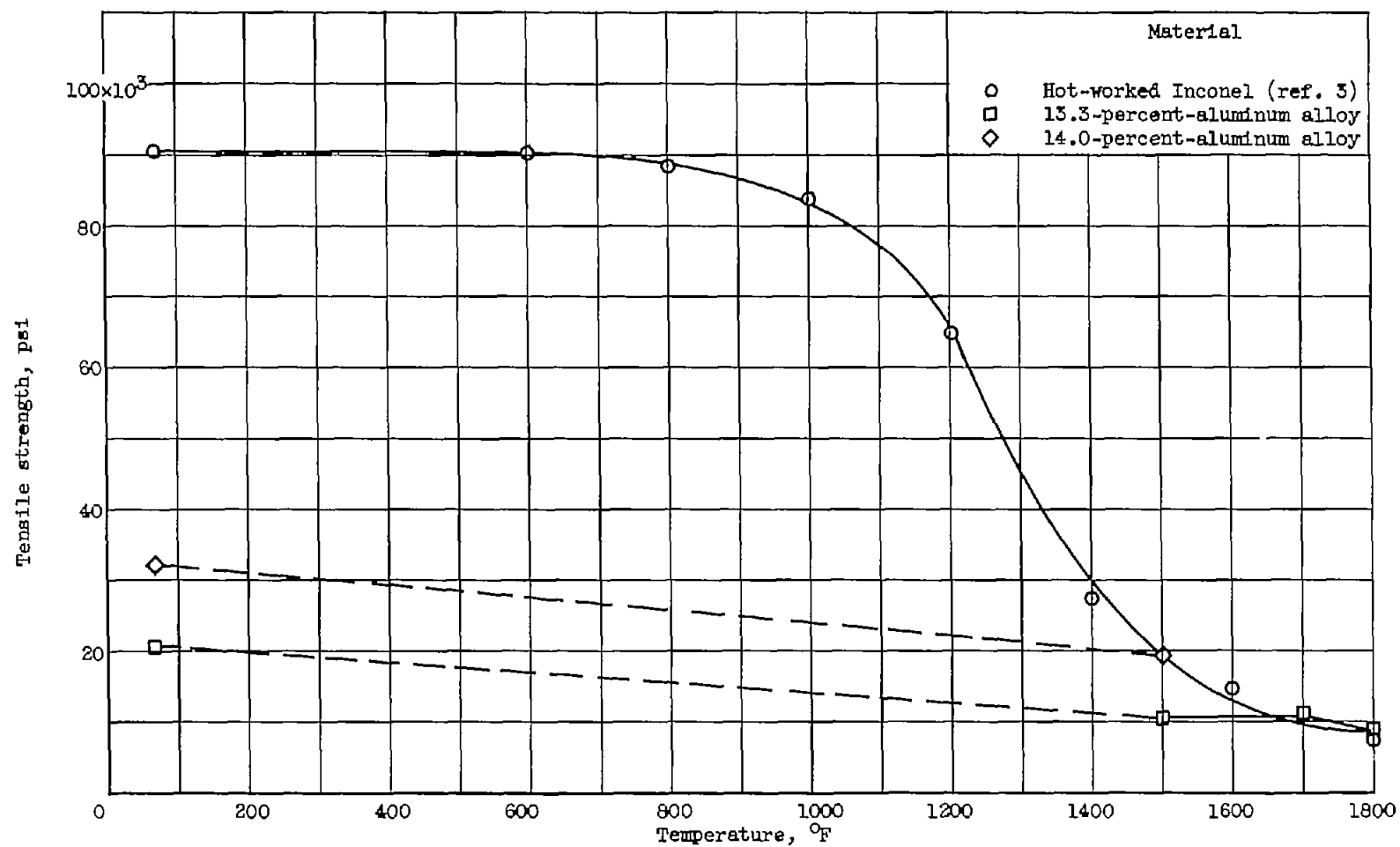
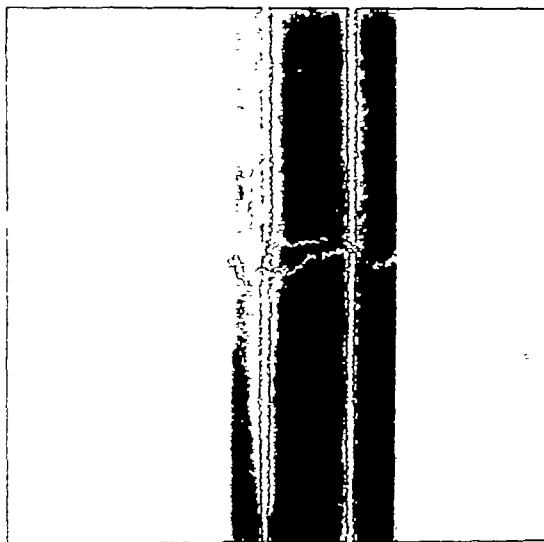


Figure 8. - Effect of temperature on tensile strength of homogenized Ni₃Al and Inconel.

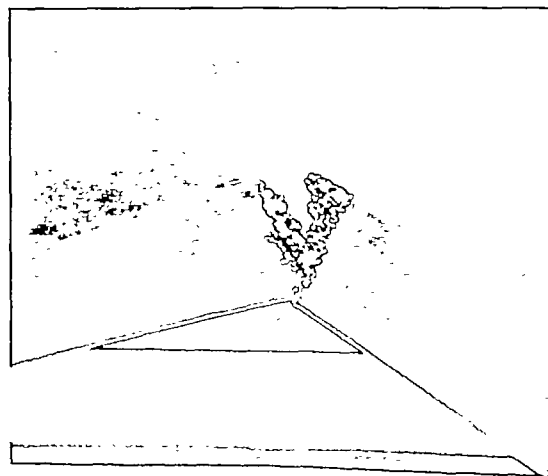
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(a) Room-temperature tensile-strength test bar. (b) Elevated-temperature tensile-strength test bar.



(c) Room-temperature tensile-strength test bar before complete separation.



(d) Impact-strength test bar.

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Figure 9. - Fibrous fracture found in Ni_3Al test bars.

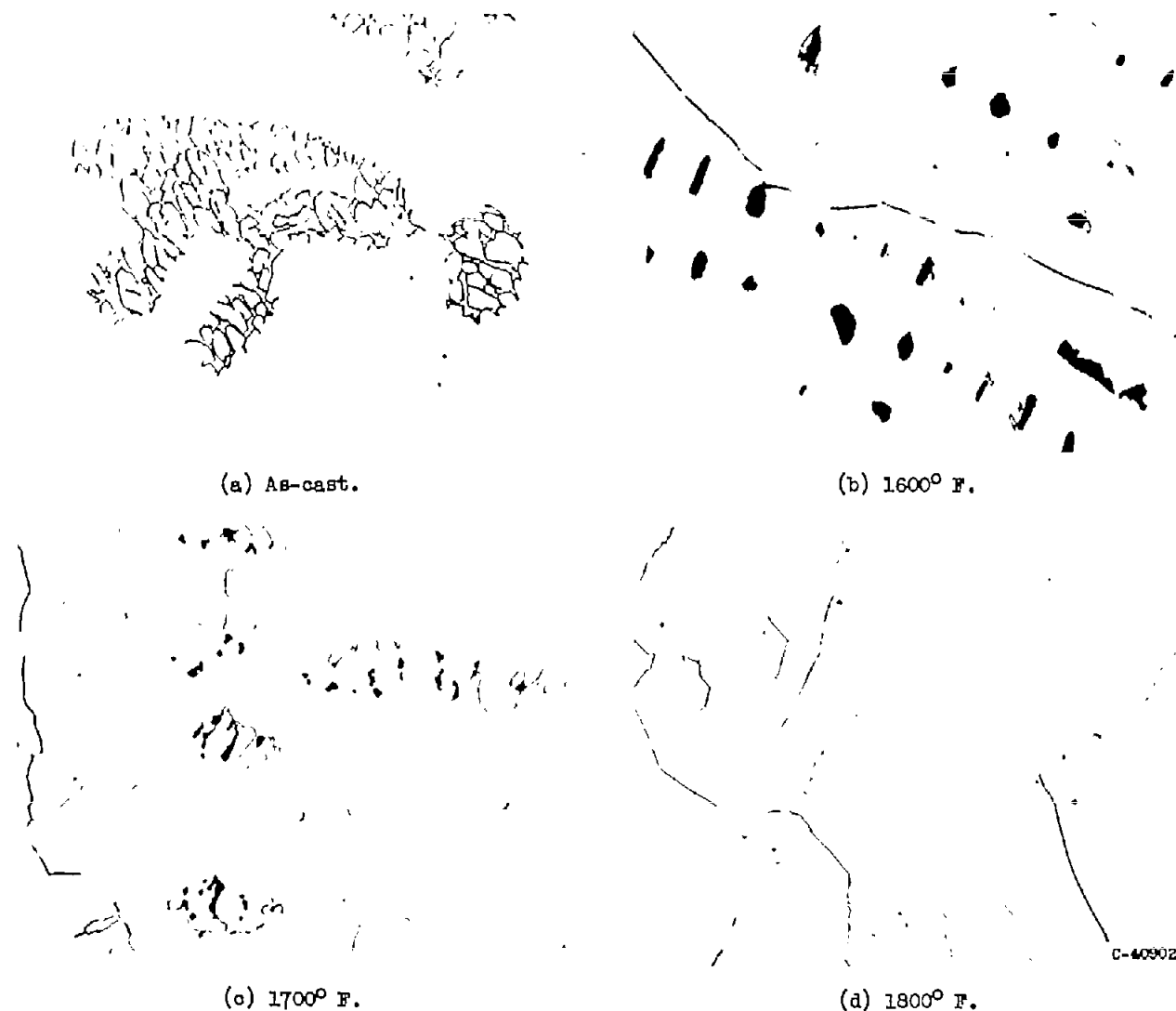


Figure 10. - Effects of 48-hour homogenization treatment at various temperatures on microstructure of stoichiometric (13.3 percent aluminum) Ni_3Al . Etchant, 1 part hydrogen tetrafluoride, 4 parts glycerine, and 4 parts water; $\times 500$.